NAVY DEPARTMENT
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THE HYDRODYNAMIC DESIGN OF A CABLE-TOWED BODY SUITABLE FOR ECONOMICAL PRODUCTION

by

Shelton M. Gay, Jr.

HYDROMECHANICS LABORATORY
RESEARCH AND DEVELOPMENT REPORT

DECEMBER 1959 REPORT 1389

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NOTATION

A	Aspect ratio
a	Slope of lift curve, $dC_L/d\alpha$
a.c.	Aerodynamic center
$a_{\Gamma = o}$	Slope of Vee-Tail lift curve for zero dihedral angle
a_o	Wing-section lift-curve slope
B	Buoyancy
b	Span
C.B.	Center of buoyancy
C.G.	Center of gravity
C_F	Generalized force coefficient
C_L	Lift coefficient
C_{L_α}	Lift-curve slope
$C_{\bar{m}_\theta}$	Pitching moment coefficient derivative with respect to angle of pitch
C_{m_ψ}	Yawing-moment coefficient
C_R	Resistance coefficient, $C_R = R\ (\frac{1}{2}\rho V^2 d)^{-1}$
C_{y_β}	Side-force coefficient derivative with respect to angle of side slip
C_{y_ψ}	Side-force coefficient derivative with respect to angle of yaw
c	Chord
D	Drag
d	Cable diameter
e	Distance the wing is offset from body centerline
F	Generalized force
g	Acceleration of gravity
i	Incidence with respect to body reference line
(k_2-k_1)	Virtual mass coefficient

L	Lift
ℓ_b	Body length
ℓ_t	Tail lever arm with respect to towpoint
M	Moment
$\overline{M}$	Resultant moment
q	Dynamic pressure, $\frac{1}{2}\rho V^2$
R	Resistance per unit length of cable towed normal to stream
r	Radius of body at longitudinal position of wing
S	Planform area
s	Cable length
T	Cable tension
T.P.	Towpoint
V	Velocity
$\forall$	Body volume
W	Weight in air
W'	Weight in water
x	Horizontal distance from point where cable enters water to the body
y	Depth of body below the water surface
Z	Total down force
α	Angle of attack
Γ	Dihedral angle
γ	Density factor
ϵ_t	Flow downwash angle at the tail
η_t	Tail efficiency factor, q_t/q
θ	Body-pitch angle with respect to stream velocity
Λ	Sweep angle
λ	Taper ratio
ρ	Mass density of the fluid
σ	Side-wash angle

τ	Lift-curve slope correction for taper-ratio
ϕ	Cable angle with respect to stream velocity
ϕ_c	Cable critical angle
ψ	Yaw angle
Ω	Body interference correction factor

Subscripts:

a	Air
b	Body
m	Model
N	Normal
p	Prototype
R	Resultant
T	Tangential
t	Tail
w	Wing
0	Bottom
1	Top

ABSTRACT

The hydrodynamic design of a specific cable-towed body suitable for economical production is presented. The general hydrodynamic requirements are listed and the design approach is described. Basin tests of a prototype body indicate that the design requirements were satisfactorily achieved.

INTRODUCTION

In November 1957, the Naval Research Laboratory requested [1] the David Taylor Model Basin to perform the hydrodynamic design for a cable-towed body to be towed from a surface ship. The body was required as part of a sonar calibration system. It was desired that the body be small, light, and of a form suitable for inexpensive fabrication. The purpose of this report is to present the design specifications, outline the hydrodynamic performance expected of the system, describe the design approach employed, and present experimental data from model basin tests to indicate the validity of the method and the degree to which the prescribed requirements were satisfactorily achieved. Further, it is hoped that the information contained herein will provide information needed to determine the suitability of this body for other applications.

DESIGN SPECIFICATIONS

In addition to the main body, the design required provision for a dome of sufficient size to house a 3-inch-diameter ball. The dome was to be attached to the underside of the main body which was to be kept free of any other projections which might interfere with the function of the dome. Other information governing the design of the complete configuration is listed in Table 1.

TABLE 1

Design Specifications

Minimum Depth of Tow, feet	50
Maximum Speed of Tow, knots	15
Cable Diameter, inches	0.30
Cable Weight in Sea Water, pounds per foot	0.13
Minimum Internal Dimensions of the Body	
Length, inches	14
Diameter, inches	3

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[1] References are listed on page 22.

DESIGN PROCEDURE

The performance required of this body did not appear to be unusual. Approximate, but direct, design techniques were therefore used. This approach seemed justified since any error in the depth of tow resulting from deviation of the developed force from design value can be compensated for by changing the length of the tow cable, as this parameter was not fixed. The steps taken in the design process were as follows:

1. The forces required to obtain the specified depth of tow were computed as a function of cable length.

2. A hydrodynamically suitable body shape of a size sufficient to provide the required internal volume was evolved.

3. A wing was designed to provide the required down force. An approximate correction for the effect of wing-body interference was made, but the stabilizer contribution to the total force was neglected.

4. Stabilizing surfaces were designed taking into account the destabilizing effect of the wing and body.

These steps are discussed in the following sections in the order stated. The dynamics of the system were not investigated since experience indicates that almost all statically stable towed bodies of this type are also dynamically stable.

CABLE FORCES

The towing configuration is shown schematically in Figure 1. The cable tension, T_o, required to position the submerged end of the tow cable at a 50-foot depth was computed by the methods of Reference 3. Specified and derived quantities required for this computation are listed as follows: *

V	-	15 knots
R	-	19.3 pounds per foot
ϕ_c	-	4 degrees
ϕ_o	-	72 degrees
s	-	100 to 250 feet

A value of the cable critical angle, $\phi_c = 4$ degrees, rather than the actual value of $\phi_c = 4.75$ degrees was selected to simplify the computation. The use of the lower value of ϕ_c results in a slight overestimate of the required force. The drag per unit length of the cable when towed normal to the stream, R, was computed from the standard equation

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* Symbols are listed on page iv.

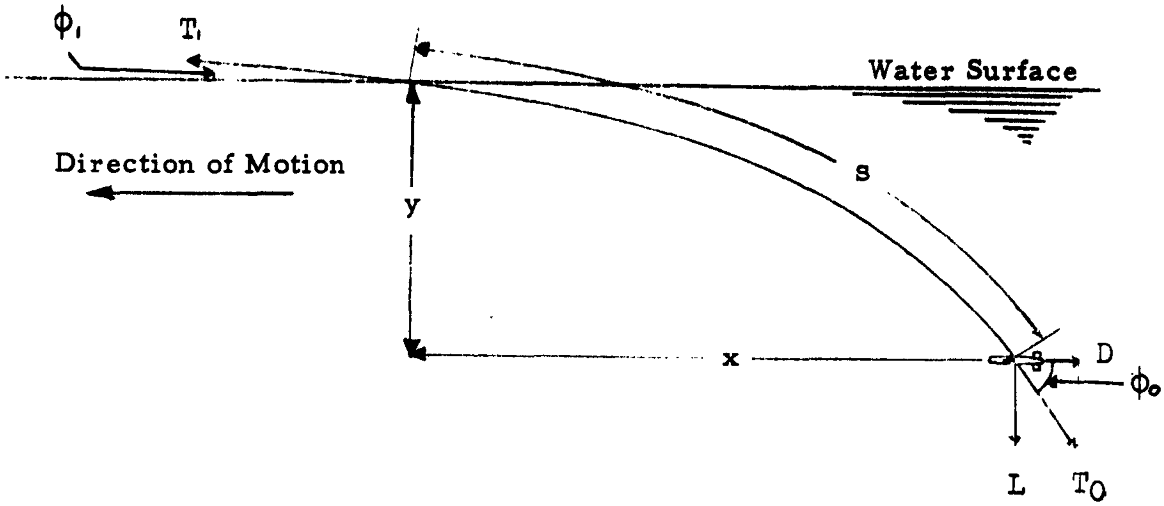

Figure 1- The Towing Configuration

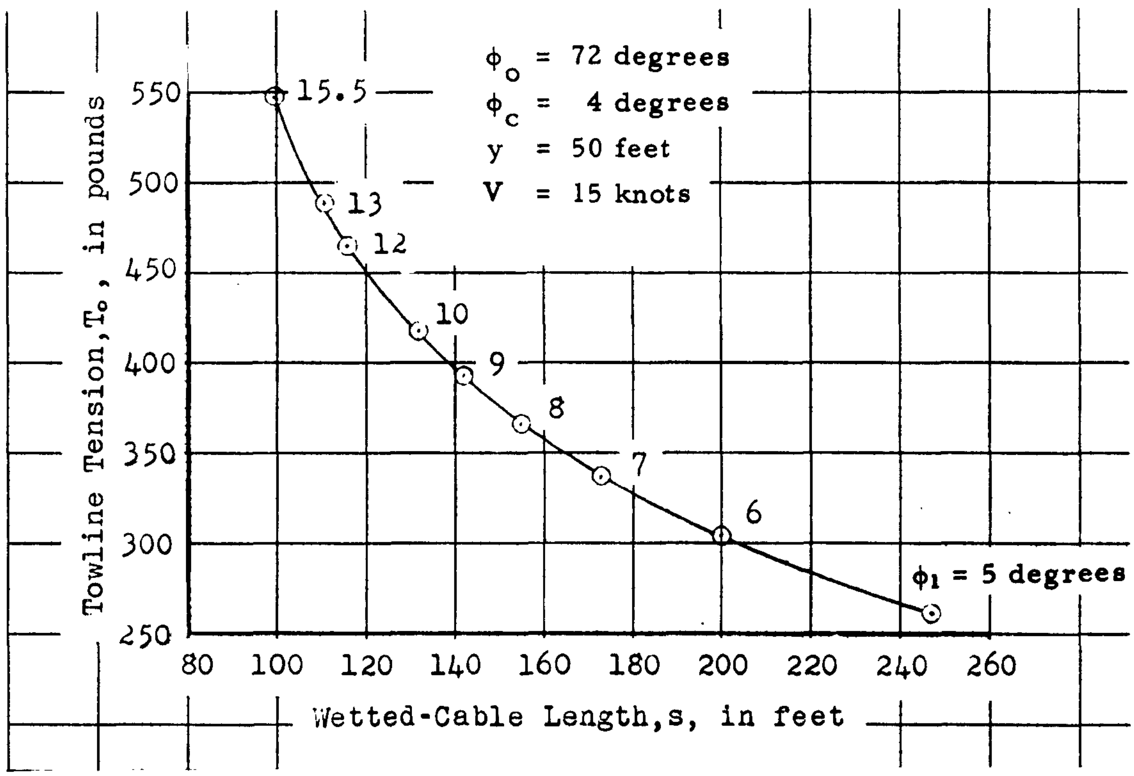

Figure 2 - Variation of Towline Tension with Wetted-Cable Length

$$R = C_R \ (\rho/2) \ dV^2 \qquad [1]$$

where ρ was taken as 2 slugs per cubic foot and C_R was taken as 1.2. The value of the cable angle, $\phi_o = 72$ degrees, was selected as being conservative since the design of a body with a down-force to drag ratio of about three is not difficult. The result of the computation is shown in Figure 2 as a plot of T_o as a function of s for constant ϕ_o. It may be noted that, within the range covered, doubling the length of the tow cable effects a substantial reduction in the required force.

GENERAL CONFIGURATION

A general body configuration was evolved based on the requirement that it be suitable for inexpensive fabrication and yet have reasonable hydrodynamic performance. The body shape was selected primarily on the basis of past experience. The resultant form, which is shown by sketch in Figure 3, is similar to that used for the body of the David Taylor Model Basin Knotmeter.[4] It consists of a cylindrical middle body, ellipsoidal nose, and conical tail. The overall fineness ratio is 4.0. The maximum diameter of 5.56 inches was chosen to correspond to a pipe of standard size with an inside diameter which would be sufficient to provide for inserting a 14-inch length of standard 3.5-inch-diameter pipe and allow enough clearance for cable-runs to a ventrally mounted transponder.

A wing of rectangular planform was selected for ease of fabrication. The slight loss in efficiency resulting from this choice is of little consequence due to the initial assumption of a low lift-drag ratio. For further simplicity, it was decided to make the wing solid of unit construction and to attach it to the upper side of the body. To avoid unsteady flow about the wing-body junction, the wing was fitted with the pressure side coincident with the top of the body. It was further decided to use a highly cambered airfoil section so that the angle of incidence with respect to the body could be kept small. The flat undersurface of such a section also provides an excellent reference for alignment.

Since the use of a tail which protruded into the region below the body was precluded, a vee-tail was selected. The vee-tail also has the advantage that no part of the stabilizer lies in the wake of the tow cable and only two fins need be manufactured. A rectangular planform was also selected for the fins.

An inexpensive trim control was obtained* by using the outboard section of the stabilizers as all-movable flaps.

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* Suggested by Mr. Haisfield of the Naval Research Laboratory.

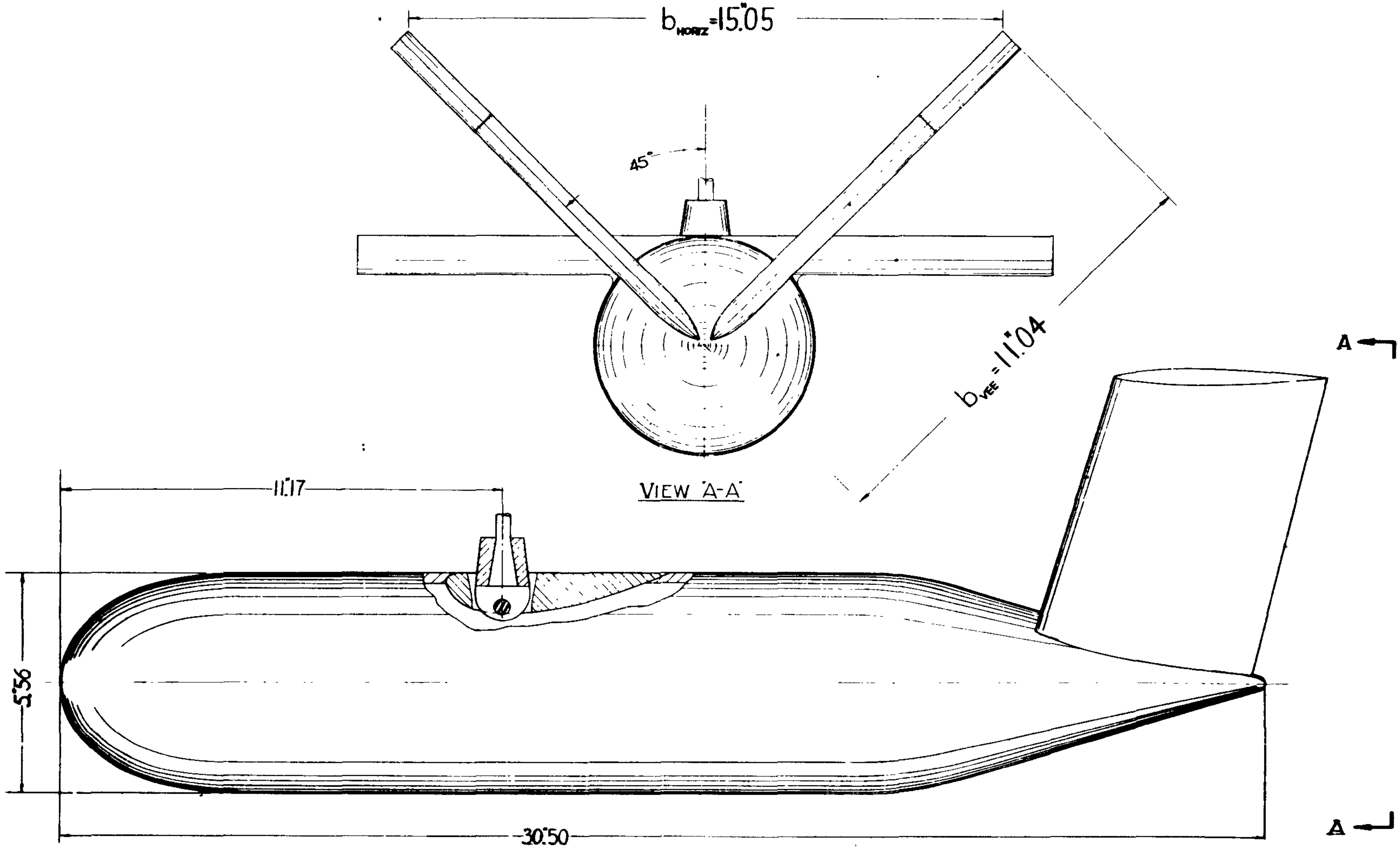


Figure 3 - General Configuration of the Prototype "Broomstick" Body

WING DESIGN

It was desired to keep both the wing area and cable length reasonably small. Since for constant ϕ_o, the required wing area is directly related to, and the cable length, s, is approximately inversely related to the tension, T_o, as shown in Figure 2, both objectives cannot be achieved. For this design, however, the emphasis was placed on obtaining a small light-weight body. A value of s = 200 feet was therefore selected to provide a reasonable balance between the two quantities.

For s = 200 feet, a value of T_o = 305 pounds acting at ϕ_o = 72 degrees is required. The down force, Z, is then

$$Z = T_o \sin \phi_o = 290 \text{ pounds}. \qquad [2]$$

The weight of the body in water, W', was estimated to be about 20 pounds. The required lift, L, is thus

$$L = Z - W' = 270 \text{ pounds}. \qquad [2.1]$$

The lift developed by a wing which intersects a cylindrical fuselage of infinite length may be written in the form[5,6]

$$L = a_w \alpha_w q S_w \Omega. \qquad [3]$$

Values must now be assigned to each parameter in Equation [3] in order to compute the wing area. From the maximum speed requirement and Equation [2.1], L/q is found to be 0.422 square foot. The lift-curve slope, a_w, is a function of planform parameters and the wing-section lift-curve slope, a_o. Planform parameters that must be selected are the taper ratio, λ; aspect ratio, A; sweep angle, Λ; and dihedral angle, Γ. Selection of a rectangular planform fixes values of two of these parameters, namely, $\lambda = 1$, $A = 0$. Zero dihedral was selected to avoid complicated fabrication of the wing. The reservation was made, however, that this might be changed later if stability requirements made it appear desirable.

With these considerations in mind, the U.S.A. - 35 A airfoil[7] was selected for the wing. From Figure 28 of Reference 7, the value of a_o was estimated to be 0.09 per degree. With the wing mounted as shown in Figure 3, the effective angle of attack α_w is 8 degrees. The value of a_w was then estimated from the relation[8]

$$\frac{1}{a_w} = \frac{1}{a_o} + \frac{1}{\pi A}\,(1 + \tau). \qquad [4]$$

The values of Ω may be computed from the relation [5, 6]

$$\Omega = 1 - \frac{r^2}{\left(\frac{b}{2}\right)^2 + e^2} = 1 - \frac{4r^2}{b^2\left[1 + \frac{4e^2}{b^2}\right]} \qquad [5]$$

where e is the distance by which the wing is offset from the centerline of the body. For most configurations, however, $b \gg e$ and the ratio $(2e/b)^2$ is negligible. With this restriction and the substitution $b^2 = AS_w$, Equation [5] becomes

$$\Omega = 1 - \frac{4r^2}{AS_w} \qquad [5.1]$$

Equation [3] may now be rewritten in the form

$$S_w = \frac{L/q}{a_w \alpha_w} + \frac{4r^2}{A}. \qquad [3.1]$$

Values of S_w were computed from Equation [3.1] for aspect ratios of 3, 4, and 5. Values of a_w were computed for each selected A using values of τ obtained from Figure 5-8, page 62, of Reference 9. Of the resulting wings, the one with an aspect ratio of 4 was selected as being the one with the most desirable combination of span and chord for structural purposes. Section and planform characteristics of the selected wing are given in Table 2; and section ordinates are given in Table 3.

STABILIZER DESIGN

Stabilizing surfaces are required to provide static or arrow stability and to produce hydrodynamic forces and moments sufficient to trim the body in pitch and yaw.

TABLE 2

Wing Specifications

Section: USA - 35 A Airfoil	
Planform: Rectangular	
Aspect Ratio, A	4
Effective lift coefficient, C_L	0.463
Effective lift curve slope, a_w, per radian	3.32
Dihedral, Γ, degrees	0
Sweep, Λ, degrees	0
Span, b, inches	22.87
Chord, c, inches	5.72

Stability in Pitch

The forces and moments acting on the configuration when at an angle θ with respect to the stream are shown in Figure 4. All quantities are shown directed in the positive sense. The total hydrodynamic moment about the towpoint is then written and reduced to coefficient form by dividing by the product of a characteristic force and lever arm. The conventional practice for a towed body is to use the product of the dynamic pressure, q, and maximum cross sectional area of the body, S_b, for the force, and the length of the body, ℓ_b, as the lever arm. The resulting equation is differentiated with respect to θ and all quantities evaluated at $\theta_{trim} = 0$. For this case, $\theta_{trim} = 0$. Consequently, considering B and W to act at the towpoint, the following equation is obtained:

$$C_{m_\theta} = 2\,(k_2 - k_1)\,\frac{\forall}{S_b \ell_b} - a_t\left(\frac{\ell_t S_t}{S_b \ell_b}\right)\eta_t\left(1 - \frac{d\epsilon_t}{d\alpha}\right). \qquad [6]$$

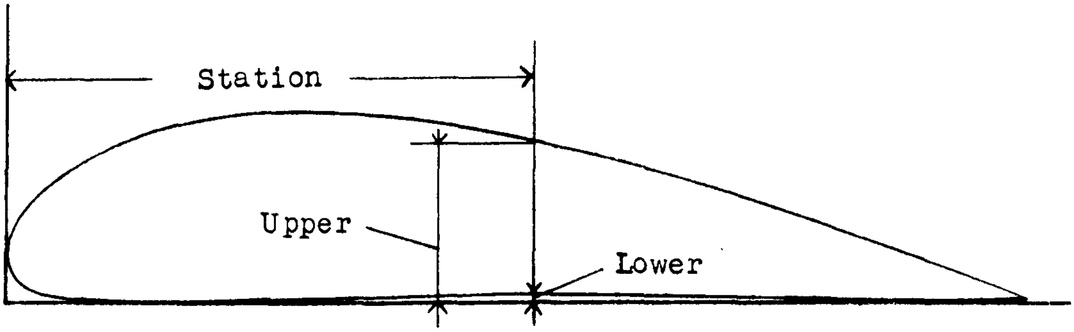
To arrive at this result it was assumed that the towpoint is placed at the aerodynamic center of the wing. The lift and drag forces thus do not contribute to the moment and the derivative of the wing moment with respect to θ is zero since it is independent of angle of attack. The tail plane is considered in the same manner, and the derivative of the moment about the aerodynamic center of the tail with respect to angle of attack disappears for the same reason. The tail arm, ℓ_t, is thus defined as the distance between the towpoint and the tail aerodynamic center. The moment due to the

TABLE 3

Offsets for the USA-35A Airfoil

Offsets in Inches

Station	Upper	Lower
.0000	.2477	.2477
.0715	.4627	.0927
.1430	.5457	.0572
.2860	.6755	.0263
.4290	.7768	.0126
.5720	.8494	.0057
.8580	.9495	.0000
1.1440	1.0142	.0046
1.7160	1.0559	.0137
2.2880	1.0233	.0229
2.8600	.9272	.0332
3.4320	.7911	.0378
4.0040	.6355	.0343
4.5760	.4507	.0286
5.1480	.2465	.0183
5.4340	.1367	.0109
5.7200	.0246	.0000



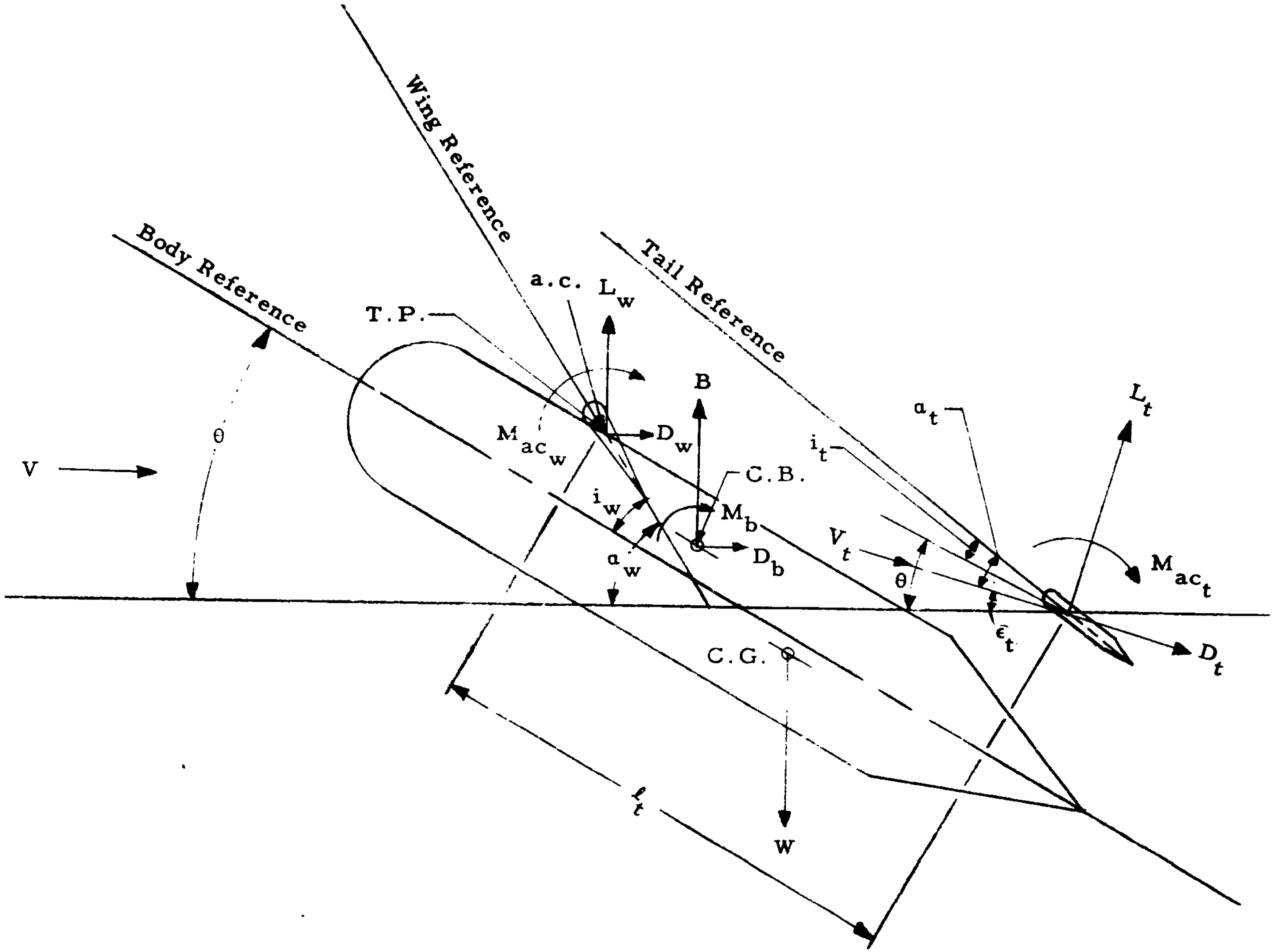


Figure 4 - Forces and Moments Acting on a Submerged Body in Level Flight at Constant Velocity

induced drag of the tail is neglected as a second-order term and the profile drag contribution of the tail is neglected as small in comparison with a_t.

The body contribution, $(k_2 - k_1)$, was estimated by the methods of Reference 10. No correction was made for the effect of the wing flow on the body moment, although this effect may be stabilizing or destabilizing according to the location of the wing along the fuselage. A technique for estimating the magnitude of the wing's effect on the body moment has been given by Multhopp[11], but the application of the method is laborious. It was therefore decided to forego this refinement and allow for such effects by computing the tail area for a high value of $C_{\overline{m}_\theta}$.

The geometry of the tail must now be fixed so that a_t can be computed and the term $(1 - \frac{d\epsilon_t}{d\alpha})$ evaluated. A vee-tail was selected for this application on basis of the considerations stated earlier. According to Reference 12, the lift-curve slope for a vee-tail is given by

$$a_t = a_{\Gamma = o} \cos^2 \Gamma \qquad [7]$$

where $a_{\Gamma = o}$ is the lift-curve slope for zero dihedral angle. $a_{\Gamma = o}$ is then evaluated on the basis of aspect ratio, sweep, and section. An approximate formula for $a_{\Gamma = o}$, in absence of detailed section information and where sweep is zero, is as follows:

$$a_{\Gamma = o} = 2\pi \frac{A}{A + 3} \qquad [8]$$

For this configuration a detailed evaluation of the term $\frac{d\epsilon_t}{d\alpha}$ would be rather laborious. There is no requirement for minimizing the tail area other than a desire to retain a compact configuration. Accordingly, it was decided to make an estimate which is certain to be conservative. The spanwise load distribution of a rectangular wing tends toward the elliptic and the tail for the subject configuration is located approximately 1.3 semi-spans downstream and thus in a region wherein the bound vortex effect is greatly diminished. For these reasons, it was decided to use the theoretical maximum value of the downwash generated by an infinite vortex sheet with an elliptic spanwise vortex distribution.

The average downwash angle at the tail plane is

$$\epsilon_t = \frac{C_L}{\pi A} \qquad [9.0]$$

and

$$\frac{d\epsilon_t}{d\alpha} = \frac{2}{\pi A} \frac{dC_L}{d\alpha} = \frac{2a_w}{\pi A} . \qquad [9.1]$$

Substituting values from Table 2 in Equation [9.1], the values $d\epsilon_t/d\alpha \simeq 0.53$ and thus $(1 - d\epsilon/d\alpha) = 0.47$ are obtained.

Equation [6] may now be solved for the tail area as a function of tail aspect ratio for any selected value of $C_{\overline{m}_\theta}$. The values required for this computation are given in Table 4.

TABLE 4

Values Required for Estimation of Tail Area

Fixed Quantities	
Body Volume, $\forall$, $(\text{feet})^3$	0.334
Virtual Mass Coefficients, (k_2-k_1)	0.8
Body Length, ℓ_b, feet	2.58
Maximum Cross-Sectional Area of Body, S_b, $(\text{feet})^2$	0.169
Distance Between Towpoint and Aerodynamic Center of Tail, ℓ_t, feet	1.25
Tail Efficiency, η_t	0.8
Dihedral Angle of Tail, Γ, degrees	45.0
Variable Quantities	
Derivative of Pitching Moment with Respect to Pitch Angle, $C_{\overline{m}_\theta}$	
Tail Aspect Ratio, A	
Tail Planform Area, S_t	
Tail Lift-Curve Slope, $a_t = \left[2\pi \frac{A}{A+3} \right] \cos^2 \Gamma$	

Substituting the values of Table 4 in Equation [6],

$$C_{\bar{m}_\theta} = \frac{2(0.8)(0.334)}{(0.169)(2.58)} - 2\pi \frac{A}{A+3} \left(\frac{1}{\sqrt{2}}\right)^2 \frac{(1.25\, S_t)(0.8)(0.47)}{(0.169)(2.58)} \qquad [6.1]$$

A series of computations was made for various assumed values of A and $C_{\bar{m}_\theta}$. When the results were interpolated, it appeared that a tail area of 0.85 square foot with an aspect-ratio of 4 would provide adequate stability. For these values, $C_{\bar{m}_\theta} \simeq -0.4$. Specifications for the stabilizer are given in Table 5.

TABLE 5

Tail Specifications

Section: Semi-circular leading edge, parallel middle section, beveled trailing edge	
Aspect Ratio, A	4.0
Half-Span at vee, b^*_{Vee}, feet	0.92
Chord, c, feet	0.462
Dihedral Angle, Γ, degrees	45.0
Taper Ratio, λ	1.0
Planform Area, S_t, $(\text{feet})^2$	0.85

Stability in Yaw

Having based the geometry of the stabilizer on the pitch requirement, a check must be made to see that it provides adequate static stability in yaw. The moment equation in yaw is identical to the one for pitch with the angle variable θ replaced by ψ, the yaw angle. Thus Equation [6] can be written in the form

$$C_{\bar{m}_\psi} = 2\,(k_2 - k_1) \frac{\forall}{S_b \ell_b} - C_{y_\psi} \left(\frac{\ell_t S_t}{S_b \ell_b}\right) \eta_t \left(1 - \frac{d\sigma}{d\psi}\right) \qquad [10]$$

where σ is the sidewash factor and C_{y_ψ} is the slope of the rudder side force versus yaw curve.

---

* See Figure 3.

The first term on the right of Equation [10] remains unchanged since the body is axially symmetric. Also S_t, ℓ_t, and η_t remained unchanged. The slope of the side-force versus yaw curve for a vee-tail may be found from the relation given by Equation [9] of Reference 12 as follows:

$$-\frac{C_{y_\beta}}{C_{L_\alpha}} = \frac{C_{y_\psi}}{C_{L_\alpha}} = K \tan^2 \Gamma \qquad [11]$$

where the angle of sideslip, β, is the negative of the yaw angle. From Figure 2 of Reference 12, K is found to be approximately 0.7.

The sidewash factor was ignored for this analysis even though it is likely that it will be destabilizing since the larger part of the fins lie in the region below the wing vortex sheet.[13] Thus, with $\frac{d\sigma}{d\psi} \simeq 0$, C_{m_ψ} is found to be -0.3.

BASIN TESTS

A prototype body was constructed by the Naval Research Laboratory and tested at the Model Basin. Several photographs of the model are shown in Figure 5.

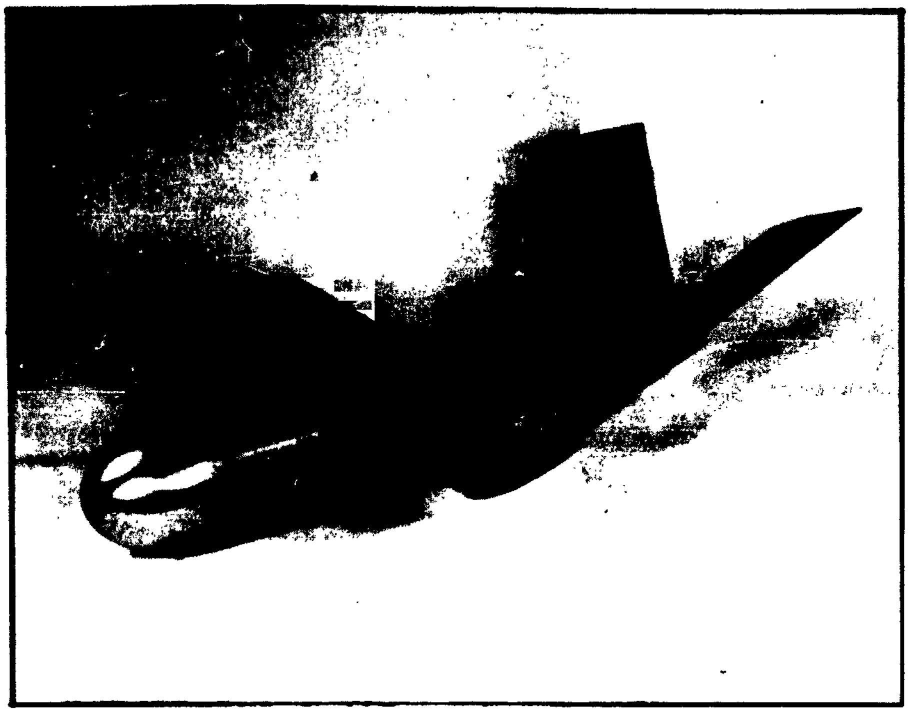
The model was tested at speeds up to 15 knots in the deep-water basin. Provision was made for measuring the attitude in pitch, the towstaff angle, and the tension. The body was towed on a 12-foot scope of cable in all cases.

Three configurations were tested:

1. Basic body (Figure 5-a, b, c).
2. Basic body with a 5-inch-diameter cylindrical dome (Figure 5d).
3. Basic body with a 5-inch-wide faired dome (Figure 5e).

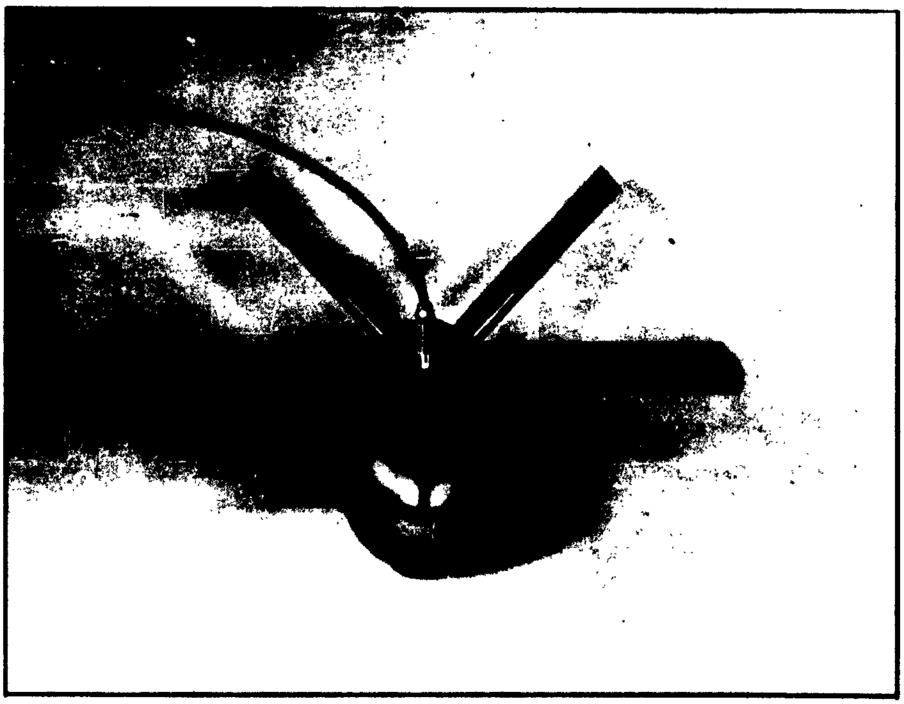
The domes shown in Figures 5d and 5e were designed and constructed by the Naval Research Laboratory. The first two configurations were towed for stability observations only. Force and angle measurements were obtained for the last configuration.

The basic configuration was stable for all speeds tested. The second configuration was unsteady in yaw. This result was not unexpected, however, and apparently was due to unsteady flow about the cylindrical dome. The last configuration towed in a steady and stable manner at all speeds tested. The body could be trimmed in pitch and yaw to obtain the desired attitude.



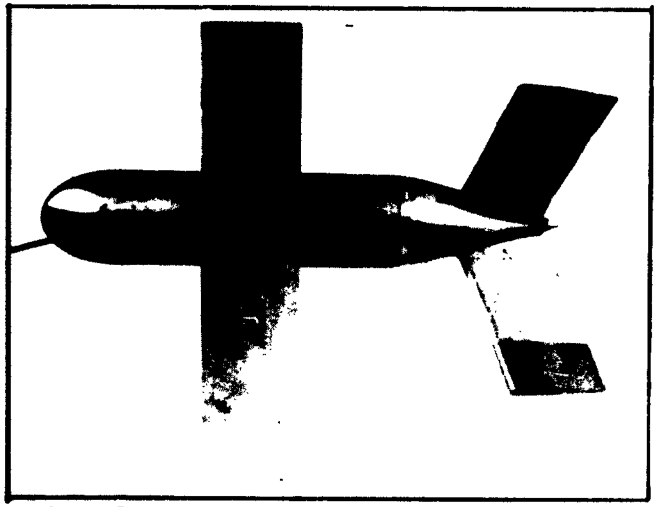
PSD 93854

(a) Basic body - side view

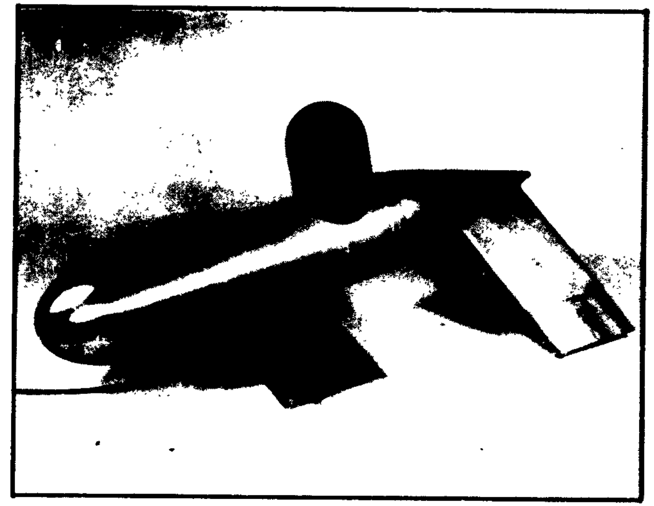


PSD 93853 (b) Basic body - front view

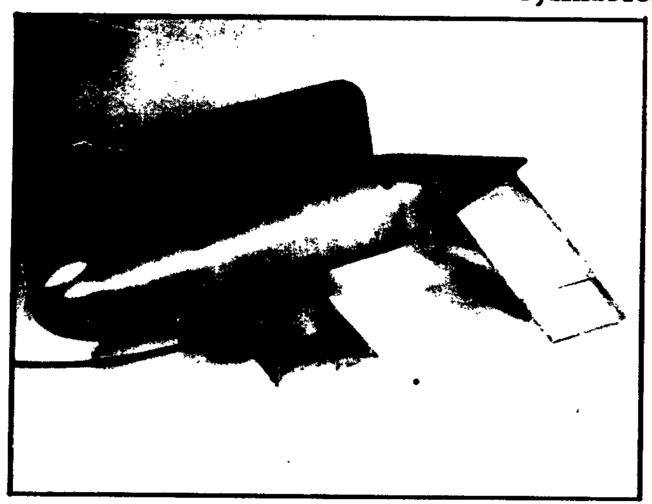
Figure 5 - Prototype "Broomstick" Body as Manufactured by the Naval Research Laboratory



PSD 93852
(c) Basic body - overhead view



PSD 93855
(d) Basic body with a 5-inch-diameter cylindrical dome



PSD 93856 (e) Basic body with 5-inch-wide streamlined dome

Figure 5 - (continued)

PROTOTYPE PERFORMANCE

The measured results were corrected to standard conditions by the method given in the Appendix. Corrected results are shown in Figure 6 for a nose-down pitch angle of 0.8 degree. With the information presented in Figure 6, the cable length required to obtain a depth of 50 feet at any speed may be computed. This computation was made for a speed of 15 knots and s was found to be 210 feet.

CONCLUSIONS

A design approach for a specific cable-towed body suitable for economical production has been presented. The approach assumes that rather large deviations from design values can be tolerated since one has freedom to vary cable scope, pitch attitude, and, within reason, the body weight in order to obtain the desired operating depth.

The satisfactory performance of the body has demonstrated that this approach was justified.

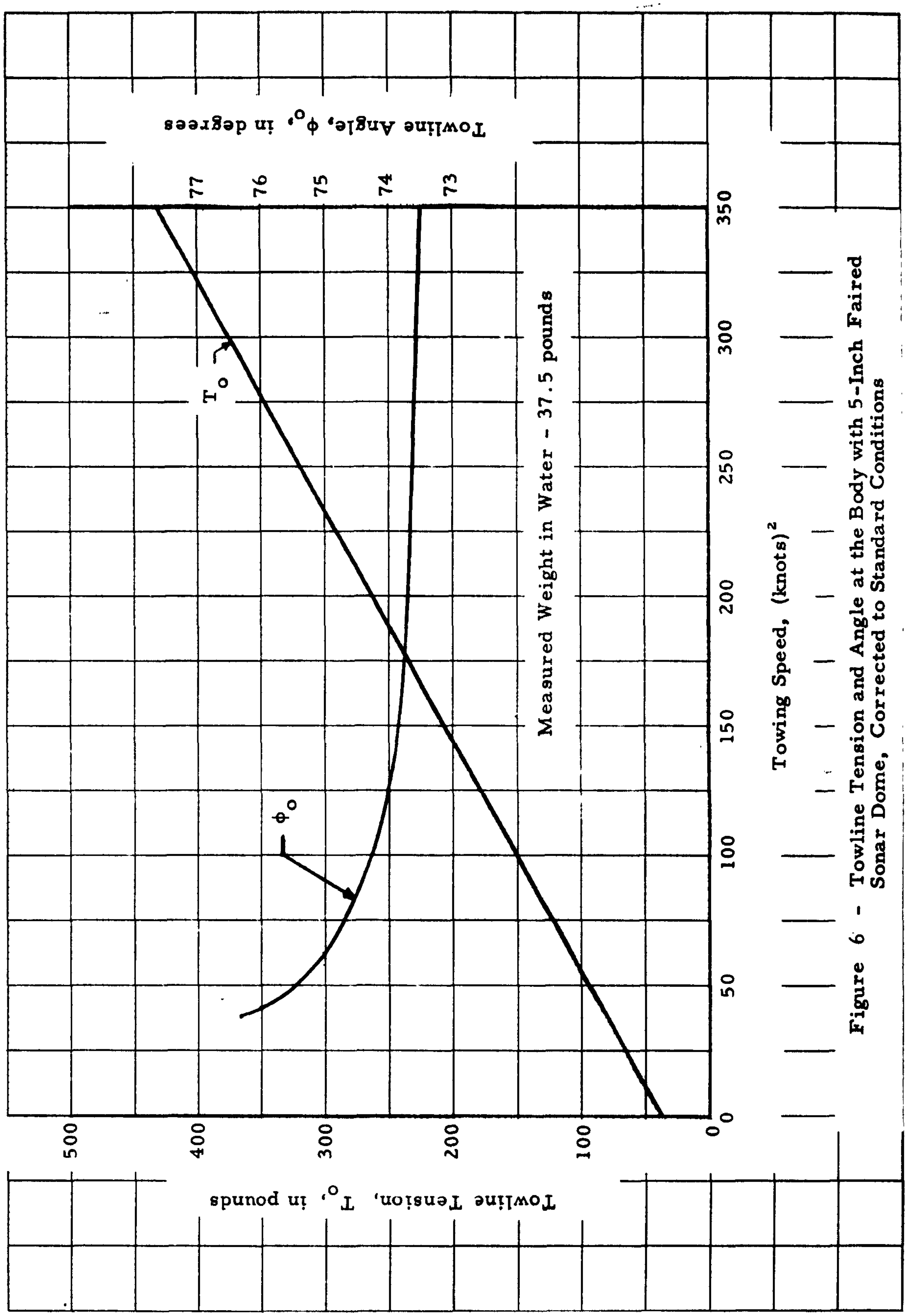


Figure 6 - Towline Tension and Angle at the Body with 5-Inch Faired Sonar Dome, Corrected to Standard Conditions

APPENDIX

CONVERSION OF BASIN TEST RESULTS TO STANDARD SEAWATER CONDITIONS* AND FULL-SCALE SPEEDS

The force acting on a body when towed at a speed, V, is the resultant of gravitational and hydrodynamic forces. The resultant force, T, may be resolved into components normal and tangential to the direction of tow by the relations

$$F_N = T \sin \phi,$$

and

$$F_T = T \cos \phi,$$

where ϕ is the angle between T and V. When the path of tow is tangential to the surface of the earth, the normal component is parallel to gravity and the tangential component becomes just the hydrodynamic drag, D. For this special case,

$$F_N = L + W', \qquad [1]$$

where L is the hydrodynamic lift and W' is the weight in water. The hydrodynamic force may be represented by a relation of the type

$$F = C_F \,(\rho/2)\, SV^2. \qquad [2]$$

If the subscripts p and m are used to designate prototype and model conditions, respectively, the ratio of prototype to model force becomes

$$\frac{F_p}{F_m} = \frac{C_{F_p}}{C_{F_m}} \frac{\rho_p}{\rho_m} \frac{S_p}{S_m} \left(\frac{V_p}{V_m}\right)^2 \qquad [3]$$

---

* 45° North Latitude, $3\frac{1}{2}$ percent salinity, 59° F.

For a deeply submerged body towed in an incompressible fluid, C_{F_p} and C_{F_m} are equal when the bodies are towed at the same Reynolds number.

For this case, $$\left(\frac{\ell V}{\nu}\right)_p = \left(\frac{\ell V}{\nu}\right)_m . \qquad [4]$$

Substituting in Equation [3] the value V_p/V_m from Equation [4], and with $\ell_p = \lambda \ell_m$ and $S_p = \lambda^2 S_m$, where λ is the linear ratio of the full scale to model size, the force ratio becomes

$$\frac{F_p}{F_m} = \frac{\rho_p}{\rho_m}\left(\frac{\nu_p}{\nu_m}\right)^2 . \qquad [5]$$

Thus, if L_m and D_m are the components of the measured hydrodynamic forces at speed V_m, the prototype forces can be found from

$$L_p = \frac{\rho_p}{\rho_m}\left(\frac{\nu_p}{\nu_m}\right)^2 L_m \qquad [6]$$

and

$$D_p = \frac{\rho_p}{\rho_m}\left(\frac{\nu_p}{\nu_m}\right)^2 D_m . \qquad [7]$$

These forces correspond to the velocity

$$V_p = \frac{1}{\lambda}\,\frac{\nu_p}{\nu_m}\,V_m . \qquad [8]$$

In this report, $\lambda = 1$, since a full-scale model was towed.

The submerged weight of the body may be found from

$$\frac{W'_p}{W'_m} = \left(\frac{\gamma - \rho_p}{\gamma - \rho_m}\right) \frac{g_p}{g_m} \qquad [9]$$

where γ is the mass density per unit volume of the object and ρ is the mass density of the fluid. γ may be found from the relation

$$\gamma = \frac{\rho_m}{1 - (W'_m/W_m)} \qquad [10]$$

where W_m and W'_m are the measured weights in air and water.

The prototype forces, F_{N_p} and F_{T_p} are

$$F_{N_p} = L_p + W'_p \qquad [11]$$

and

$$F_{T_p} = D_p \qquad [12]$$

whose resultant acts at an angle

$$Q_p = \tan^{-1} F_{N_p}/F_{T_p} \qquad [13]$$

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